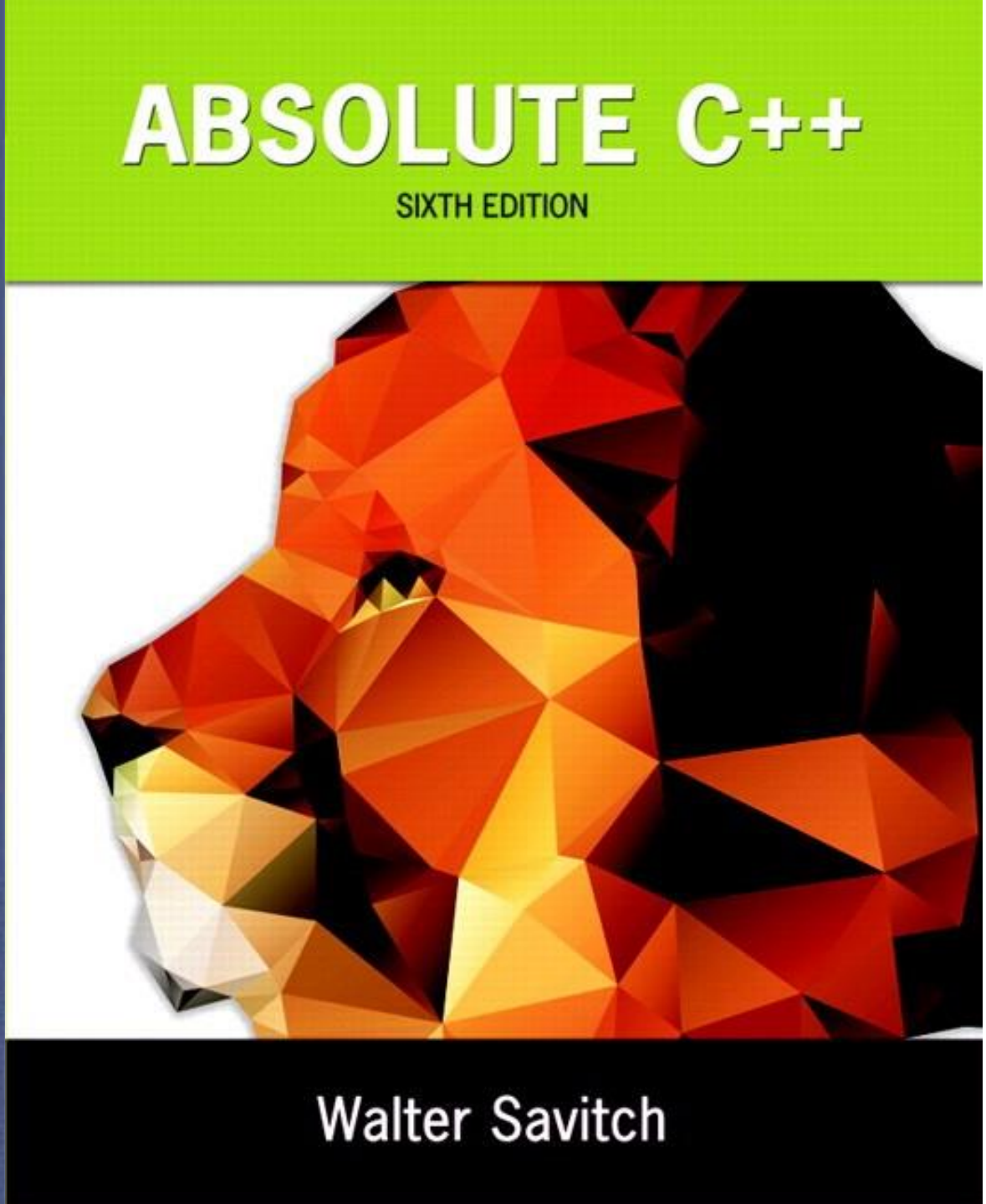



# Chapter 17

## Linked Data Structures



PEARSON

# Learning Objectives

- Nodes and Linked Lists
  - Creating, searching
- Linked List Applications
  - Stacks, queues, sets, hash tables
  - Friend classes, alternatives
- Iterators
  - Pointers as iterators
- Trees

# Introduction

- Linked list
  - Constructed using pointers
  - Grows and shrinks during run-time
  - Doubly Linked List : A variation with pointers in both directions
- Trees also use pointers
- Pointers backbone of such structures
  - Use dynamic variables
- Standard Template Library
  - Has predefined versions of some structures

# Approaches

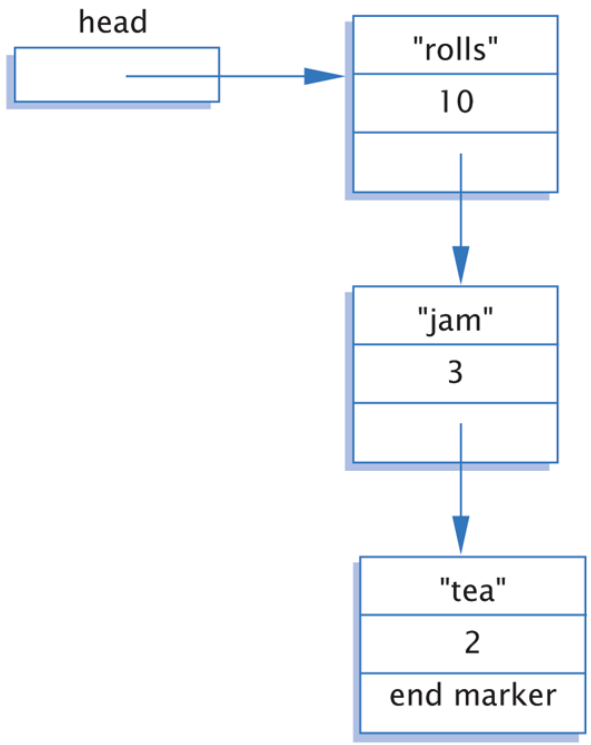
- Three ways to handle such data structures:
  1. C-style approach: global functions and structs with everything public
  2. Classes with private member variables and accessor and mutator functions
  3. Friend classes
- Linked lists will use method 1
- Stacks, queues, sets, and hash tables will use method 2
- Trees will use method 3

# Nodes and Linked Lists

- Linked list
  - Simple example of "dynamic data structure"
  - Composed of nodes
- Each "node" is variable of struct or class type that’s dynamically created with new
  - Nodes also contain pointers to other nodes
  - Provide "links"

# **Display 17.1** Nodes and Pointers

**Display 17.1 Nodes and Pointers**



# Node Definition

- struct ListNode
  {
  string item;
  int count;
  ListNode *link;
  };
  typedef ListNode* ListNodePtr;
- Order here is important!
  - Listnode defined 1st, since used in typedef
- Also notice "circularity"

# Head Pointer

- Box labeled "head" not a node:
  ListNodePtr head;
  - A simple pointer to a node
  - Set to point to 1st node in list
- Head used to "maintain" start of list
- Also used as argument to functions

# Example Node Access

- (*head).count = 12;
  - Sets *count* member of node pointed to by *head* equal to 12
- Alternate operator, ->
  - Called "arrow operator"
  - Shorthand notation that combines * and .
  - head->count = 12;
    - Identical to above
- cin >> head->item
  - Assigns entered string to *item* member

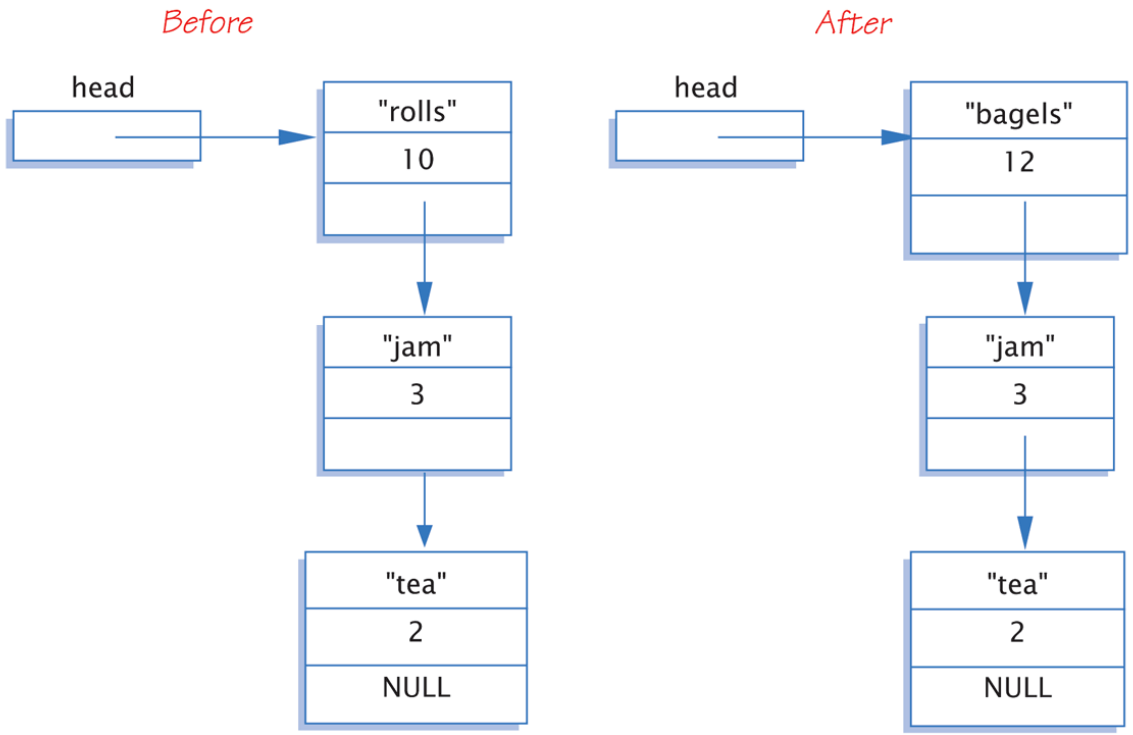
# End Markers

- Use NULL or nullptr (in C++11) for node pointer
  - Considered "sentinel" for nodes
  - Indicates no further "links" after this node
- Provides end marker similar to how we use partially-filled arrays

# Display 17.2 Accessing Node Data

**Display 17.2 Accessing Node Data**

```
head->count = 12;
head->item = "bagels";
```



# Linked List

- Lists as illustrated called linked lists
- First node called *head*
  - Pointed to by pointer named *head*
- Last node special also
  - It's member pointer variable is NULL (or nullptr in C++11)
  - Easy test for "end" of linked list

# Linked List Class Definition

- ```
  class IntNode
  {
  public:
      IntNode() { }
      IntNode(int theData, IntNode* theLink)
          : data(theData), link(theLink) { }
      IntNode* getLink()          const          {return link;}
      int getData()               const          {return data;}
      void setData(int theData)                  {data = theData;}
      void setLink(IntNode* pointer)             {link=pointer;}
  private:
      int data;
      IntNode *link;
  };
  typedef IntNode* IntNodePtr;
  ```
  ```

# Linked List Class

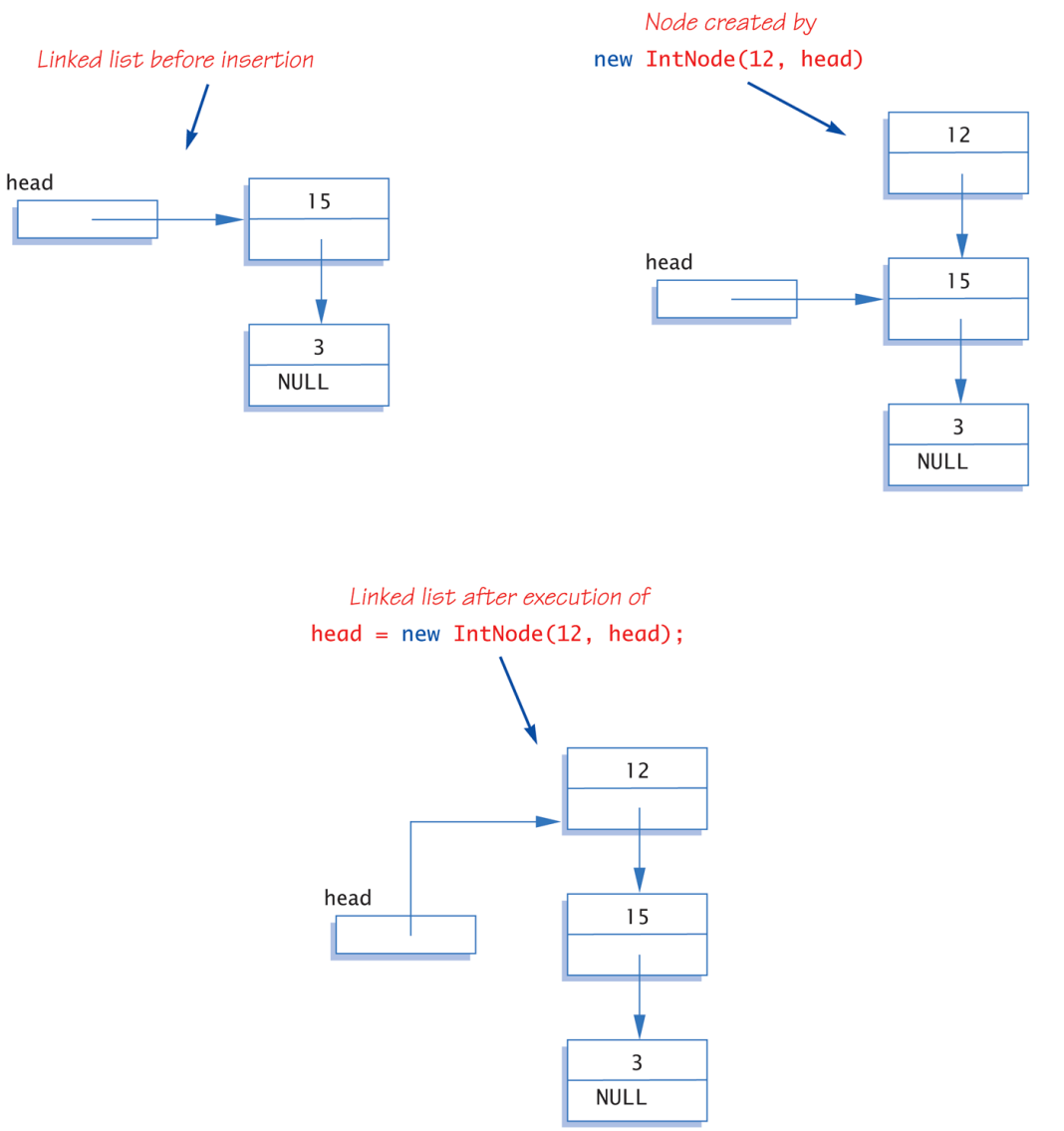
- Notice all member function definitions are inline
  - Small and simple enough
- Notice two-parameter constructor
  - Allows creation of nodes with specific data value and specified link member
  - Example:
    IntNodePtr p2 = new IntNode(42, p1);

# Create 1st Node

- IntNodePtr head;
  - Declares pointer variable *head*
- head = new IntNode;
  - Dynamically allocates new node
  - Our 1st node in list, so assigned to head
- head->setData(3);
  head->setLink(NULL);
  - Sets head node data
  - Link set to NULL since it's the only node!

# Display 17.3
Adding a Node to the Head of a Linked List

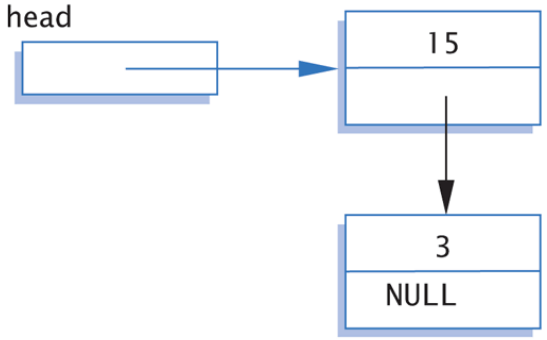
Display 17.3 **Adding a Node to the Head of a Linked List**



# Lost Nodes Pitfall:
# **Display 17.5** Lost Nodes

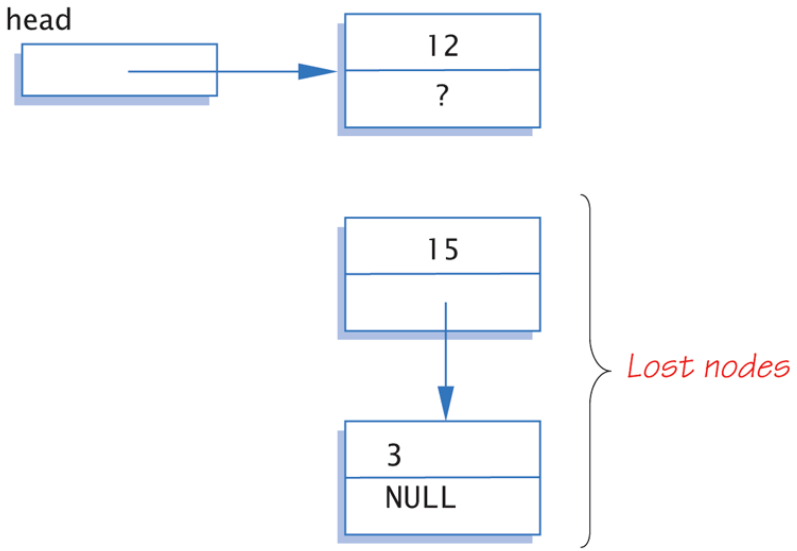
**Display 17.5 Lost Nodes**

*Linked list before insertion*



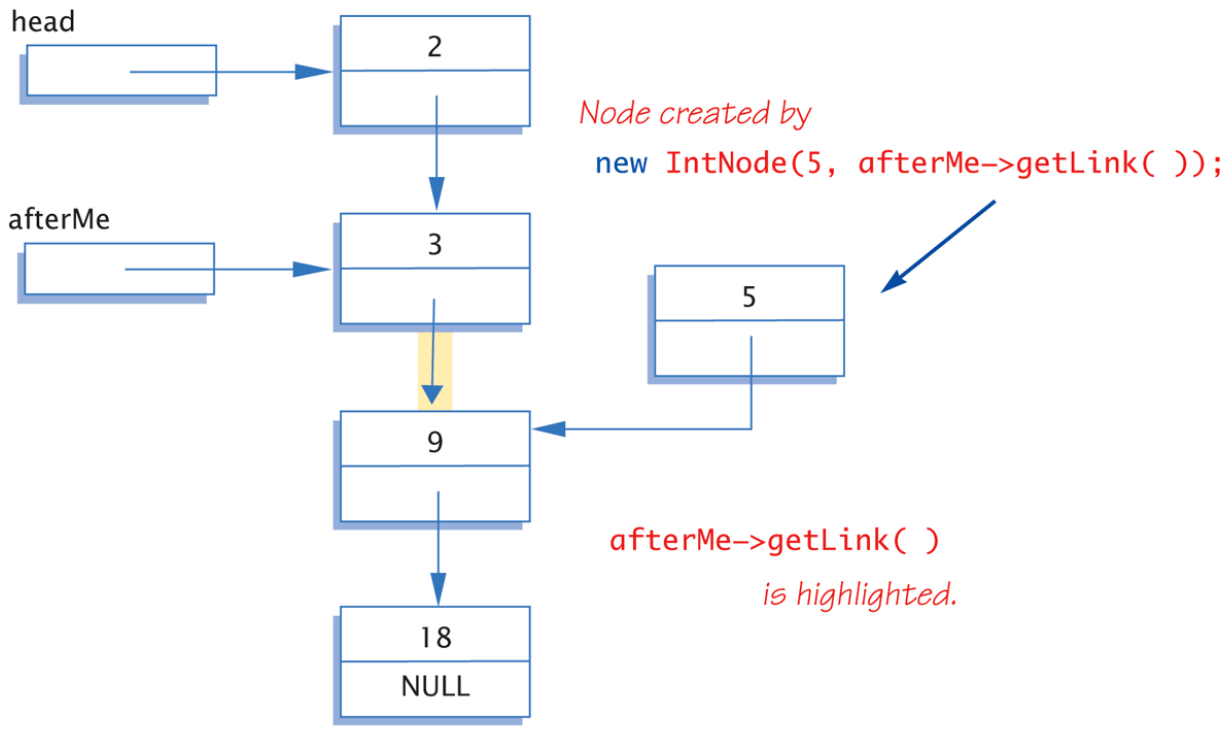

*Situation after executing*

```
head = new IntNode;
head->setData(theData);
```

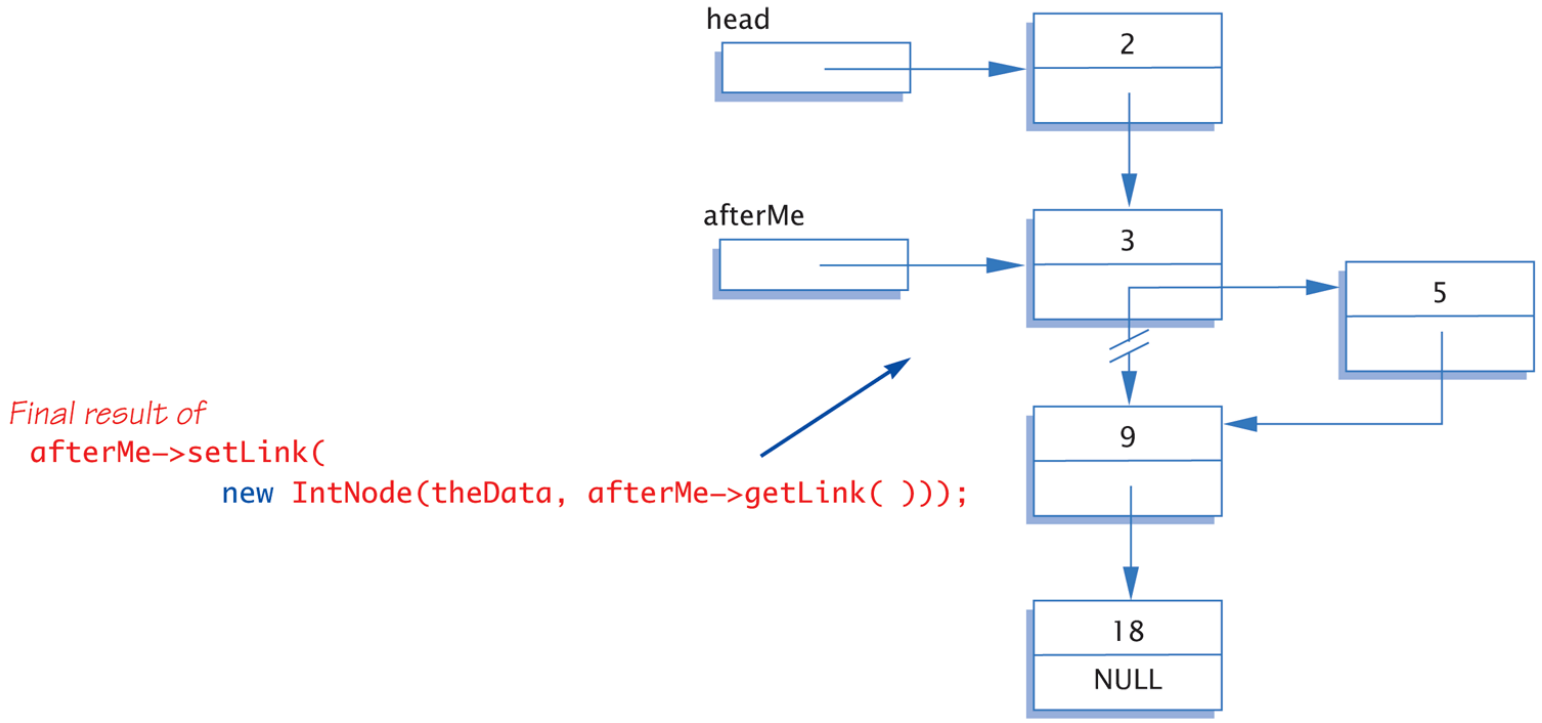


# **Display 17.6** Inserting in the Middle of a Linked List (1 of 2)

**Display 17.6 Inserting in the Middle of a Linked List**

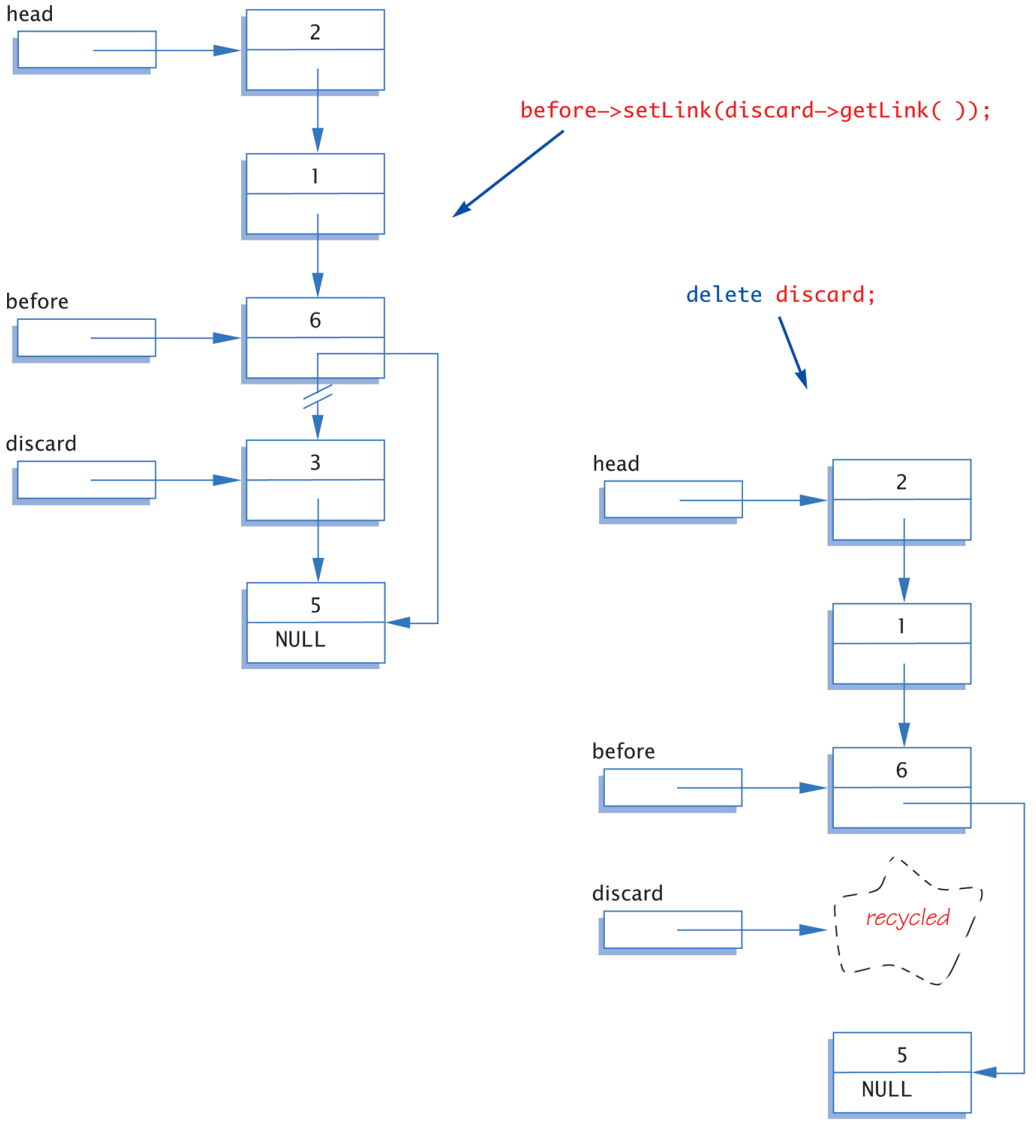


# **Display 17.6** Inserting in the Middle of a Linked List (2 of 2)



# Display 17.7 Removing a Node

Display 17.7 **Removing a Node**



# Searching a Linked List

- Function with two arguments:
  IntNodePtr search(IntNodePtr head, int target);
  **//Precondition: pointer head points to head of**
  **//linked list.  Pointer in last node is NULL.**
  **//If list is empty, head is NULL**
  **//Returns pointer to 1st node containing target**
  **//If not found, returns NULL**
- Simple "traversal" of list
  - Similar to array traversal

# Pseudocode for search Function

- while (here doesn't point to target node or
  last node)
  {
  Make here point to next node in list
  }
  if (here node points to target)
  return here;
  else
  return NULL;

# Algorithm for search Function

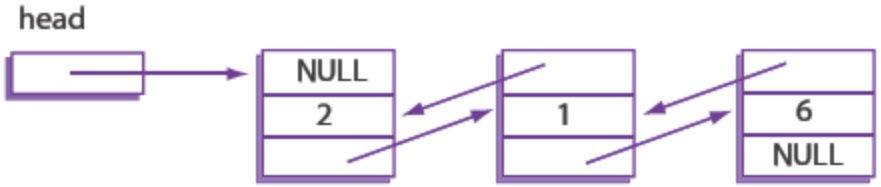
- while (here->getData() != target &&
  here->getLink() != NULL)
  here = here->getLink();

  if (here->getData() == target)
  return here;
  else
  return NULL;
- Must make "special" case for empty list
  - Not done here

# Doubly Linked Lists

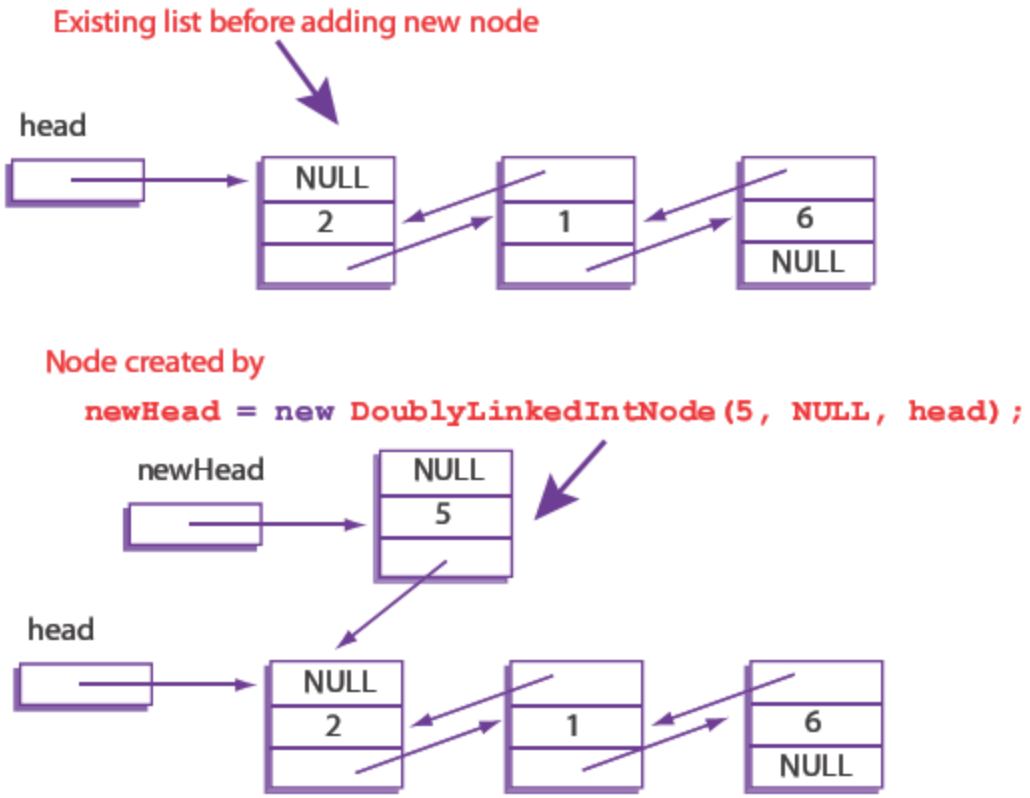
- What we just described is a singly linked list
  - Can only follow links in one direction
- Doubly Linked List
  - Links to the next node and another link to the previous node
  - Can follow links in either direction
  - NULL signifies the beginning and end of the list
  - Can make some operations easier, e.g. deletion since we don’t need to search the list to find the node before the one we want to remove

# Doubly Linked Lists

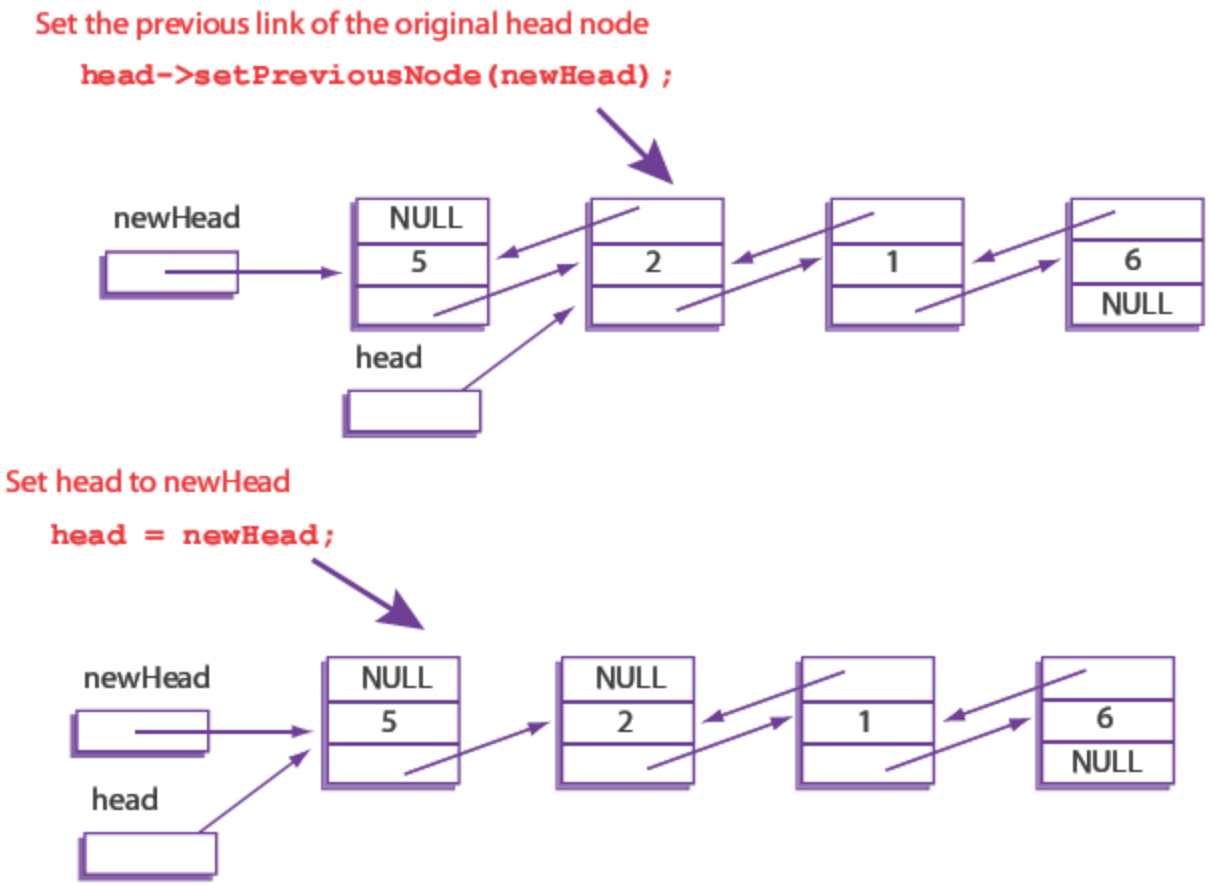



```
class DoublyLinkedIntNode
{
public:
    DoublyLinkedIntNode ( ){}
    DoublyLinkedIntNode (int theData, DoublyLinkedIntNode* previous,
                         DoublyLinkedIntNode* next)
            : data(theData), nextLink(next), previousLink(previous) {}
    DoublyLinkedIntNode* getNextLink( ) const { return nextLink; }
    DoublyLinkedIntNode* getPreviousLink( ) const { return previousLink; }
    int getData( ) const { return data; }
    void setData(int theData) { data = theData; }
    void setNextLink(DoublyLinkedIntNode* pointer) { nextLink = pointer; }
    void setPreviousLink(DoublyLinkedIntNode* pointer)
         { previousLink = pointer; }
private:
    int data;
    DoublyLinkedIntNode *nextLink;
    DoublyLinkedIntNode *previousLink;
};
typedef DoublyLinkedIntNode* DoublyLinkedIntNodePtr;
```

# Adding a Node to the Front of a Doubly Linked List (1 of 2)



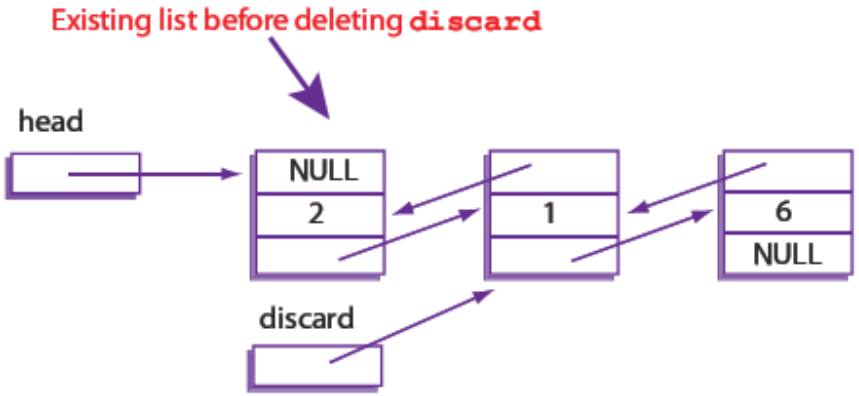
# Adding a Node to the Front of a Doubly Linked List (2 of 2)



# Deleting a Node from a Doubly Linked List

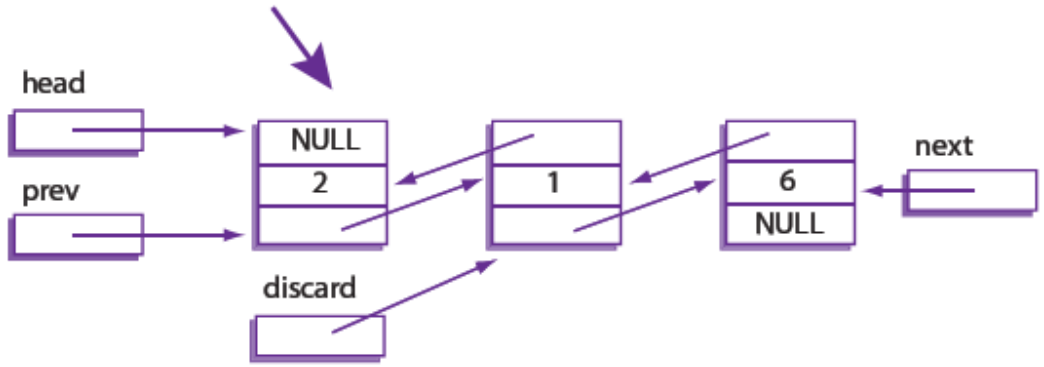
- Removing a node requires updating references on both sides of the node we wish to delete
- Thanks to the backward link we do not need a separate variable to keep track of the previous node in the list like we did for the singly linked list
  - Can access via  node->previous

# Deleting a Node from a Doubly Linked List (1 of 2)

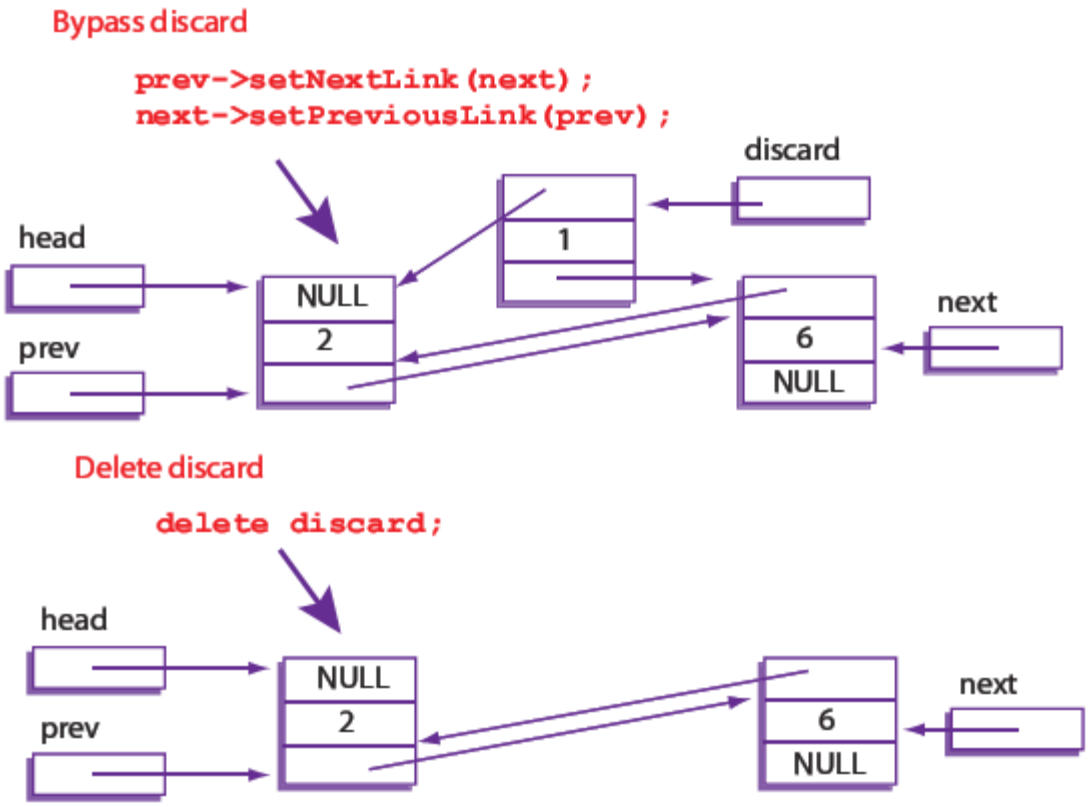



Set pointers to the previous and next nodes

```
DoublyLinkedIntNodePtr prev = discard->getPreviousLink( );
DoublyLinkedIntNodePtr next = discard->getNextLink( );
```



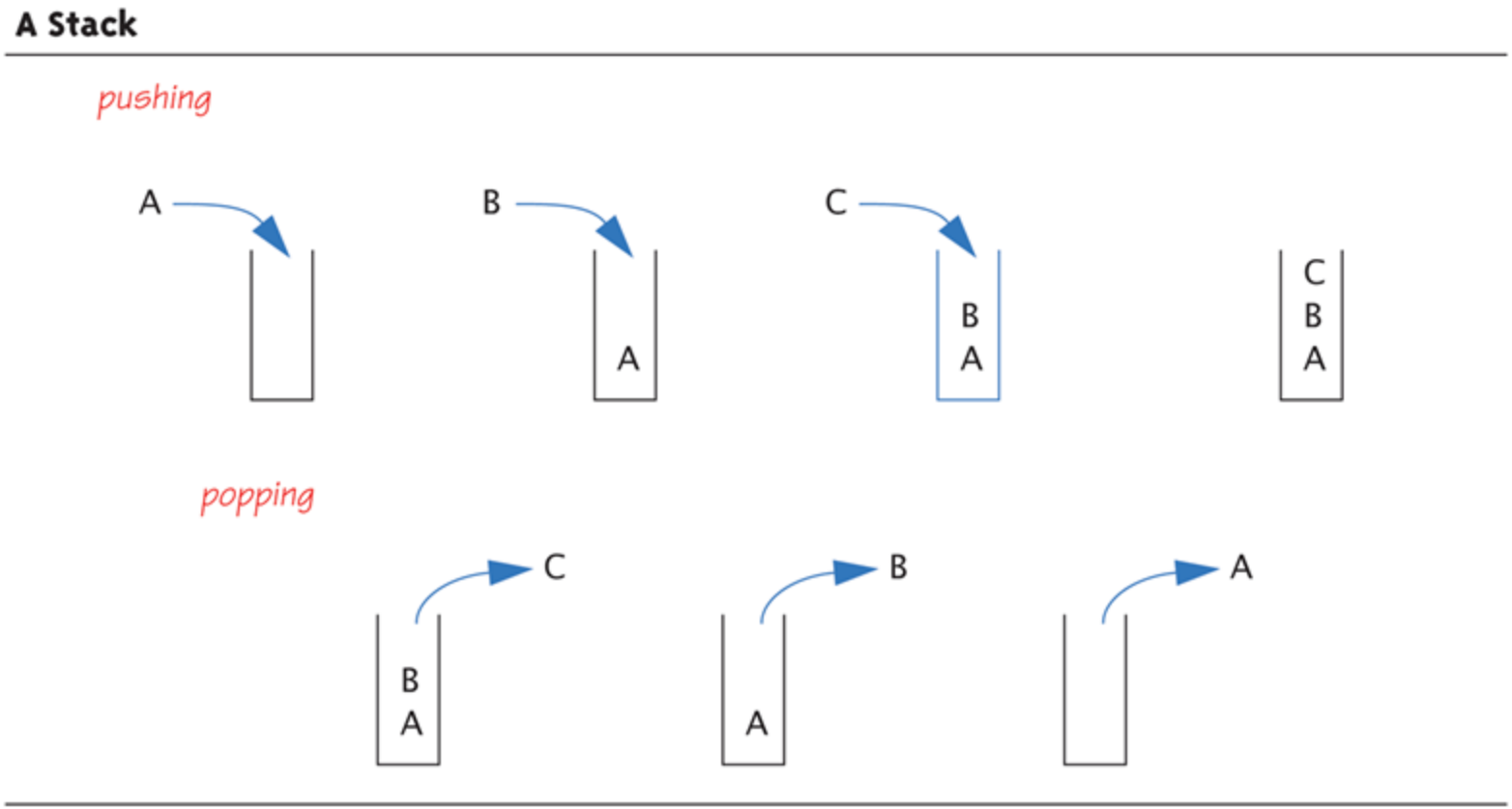
# Deleting a Node from a Doubly Linked List (2 of 2)



# Stacks

- Stack data structure:
  - Retrieves data in reverse order of how stored
  - LIFO – last-in/first-out
  - Think of like "hole in ground"
- Stacks used for many tasks:
  - Track C++ function calls
  - Memory management
- Our use:
  - Use linked lists to implement stacks

# A Stack—Graphic:
# **Display 17.12** A Stack



# **Display 17.17** Interface File for a Stack Template Class (1 of 2)

**Interface File for a Stack Template Class**

```
1   //This is the header file stack.h. This is the interface for the class
2   //Stack, which is a template class for a stack of items of type T.
3   #ifndef STACK_H
4   #define STACK_H

5   namespace StackSavitch
6   {
7       template<class T>
8       class Node
9       {
10      public:
11          Node(T theData, Node<T>* theLink) : data(theData), link(theLink){}
12          Node<T>* getLink( ) const { return link; }
13          const T getData( ) const { return data; }
14          void setData(const T& theData) { data = theData; }
15          void setLink(Node<T>* pointer) { link = pointer; }
16      private:
17          T data;
18          Node<T> *link;
19      };
```

*You might prefer to replace the parameter type* T *with* `const T&`.

# **Display 17.17** Interface File for a Stack Template Class (2 of 2)

**Interface File for a Stack Template Class**

```
20          template<class T>
21      class Stack
22      {
23    public:
24          Stack( );
25          //Initializes the object to an empty stack.
26          Stack(const Stack<T>& aStack);
27          Stack<T>& operator =(const Stack<T>& rightSide);
28          virtual ~Stack( );
29          void push(T stackFrame);
30          //Postcondition: stackFrame has been added to the stack.
31          T pop( );
32          //Precondition: The stack is not empty.
33          //Returns the top stack frame and removes that top
34          //stack frame from the stack.
35          bool isEmpty( ) const;
36          //Returns true if the stack is empty. Returns false otherwise.
37      private:
38          Node<T> *top;
39      };
40  }//StackSavitch
41  #endif //STACK_H
```

*Copy constructor*

*The destructor destroys the stack and returns all the memory to the freestore.*

# Stack Template Class Driver: **Display 17.18** Program Using the Stack Template Class (1 of 3)

**Program Using the Stack Template Class**

```
1  //Program to demonstrate use of the Stack template class.
2  #include <iostream>
3  #include "stack.h"
4  #include "stack.cpp"
5  using std::cin;
6  using std::cout;
7  using std::endl;
8  using StackSavitch::Stack;
```

(continued)

# Stack Template Class Driver: **Display 17.18** Program Using the Stack Template Class (2 of 3)

**Program Using the Stack Template Class**

```
 9  int main( )
10  {
11      char next, ans;

12      do
13      {
14          Stack<char> s;
15          cout << "Enter a line of text:\n";
16          cin.get(next);
17          while (next != '\n')
18          {
19              s.push(next);
20              cin.get(next);
21          }
```

# Stack Template Class Driver: **Display 17.18** Program Using the Stack Template Class (3 of 3)

```
22          cout << "Written backward that is:\n";
23          while ( ! s.isEmpty( ) )
24              cout << s.pop( );
25          cout << endl;

26          cout << "Again?(y/n): ";
27          cin >> ans;
28          cin.ignore(10000, '\n');
29      }while (ans != 'n' && ans != 'N');

30      return 0;
31  }
```

**SAMPLE DIALOGUE**

```
Enter a line of text:
straw
Written backward that is:
warts
Again?(y/n): y
Enter a line of text:
I love C++
Written backward that is:
++C evol I
Again?(y/n): n
```

*The `ignore` member of `cin` is discussed in Chapter 9. It discards input remaining on the line.*

# Stack Push and Pop

- Adding data item to stack → push
  - Considered "pushing" data onto stack
  - Recall: goes to "top" of stack
- Removing data item from stack → pop
  - Considered "popping" item off stack
  - Recall: removed from "top" of stack

# Queues

- Another common data structure:
  - Handles data in first-in/first-out manner (FIFO)
  - Items inserted to end of list
  - Items removed from front
- Representation of typical "line" forming
  - Like bank teller lines, movie theatre lines, etc.

# **Display 17.20** Interface File for a Queue Template Class (1 of 3)

**Interface File for a Queue Template Class**

```
1
2   //This is the header file queue.h. This is the interface for the class
3   //Queue, which is a template class for a queue of items of type T.
4   #ifndef QUEUE_H
5   #define QUEUE_H

6   namespace QueueSavitch
7   {
8       template<class T>
9       class Node
10      {
11      public:
12          Node(T theData, Node<T>* theLink) : data(theData), link(theLink){}
13          Node<T>* getLink( ) const { return link; }
14          const T getData( ) const { return data; }
15          void setData(const T& theData) { data = theData; }
16          void setLink(Node<T>* pointer) { link = pointer; }
17      private:
18          T data;
```

*This is the same definition of the template class* Node *that we gave for the stack interface in Display 17.13. See the tip "A Comment on Namespaces" for a discussion of this duplication.*

(continued)

# **Display 17.20** Interface File for a Queue Template Class (2 of 3)

**Interface File for a Queue Template Class**

```
19          Node<T> *link;
20      };
21      template<class T>
22      class Queue
23      {
24      public:
25          Queue( );
26          //Initializes the object to an empty queue.
27          Queue(const Queue<T>& aQueue);
28          Queue<T>& operator =(const Queue<T>& rightSide);
29          virtual ~Queue( );
30
```

*You might prefer to replace the parameter type* T *with* `const T&`.

*Copy constructor*

*The destructor destroys the queue and returns all the memory to the freestore.*

# **Display 17.20** Interface File for a Queue Template Class (3 of 3)

```
31          void add(T item);
32          //Postcondition: item has been added to the back of the queue.

33          T remove( );
34          //Precondition: The queue is not empty.
35          //Returns the item at the front of the queue
36          //and removes that item from the queue.

37          bool isEmpty( ) const;
38          //Returns true if the queue is empty. Returns false otherwise.
39      private:
40          Node<T> *front;//Points to the head of a linked list.
41                         //Items are removed at the head
42          Node<T> *back;//Points to the node at the other end of the linked list.
43                        //Items are added at this end.
44      };

45  }//QueueSavitch

46  #endif //QUEUE_H
```

# Queue Template Class Driver: **Display 17.21** Program Using the Queue Template Class

```
12      do
13      {
14          Queue<char> q;
15          cout << "Enter a line of text:\n";
16          cin.get(next);
17          while (next != '\n')
18          {
19              q.add(next);
20              cin.get(next);
21          }


22          cout << "You entered:\n";
23          while ( ! q.isEmpty( ) )
24              cout << q.remove( );
25          cout << endl;

26          cout << "Again?(y/n): ";
27          cin >> ans;
28          cin.ignore(10000, '\n');
29      }while (ans != 'n' && ans != 'N');
```

# Hash Tables

- A hash table or hash map is a data structure that efficiently stores and retrieves data from memory
- Here we discuss a hash table that uses an array in combination with singly linked lists
- Uses a hash function
  - Maps an object to a key
  - In our example, a string to an integer

# Simple Hash Function for Strings

- Sum the ASCII value of every character in the string and then compute the modulus of the sum using the size of the fixed array.

```
int computeHash(string s)
{
  int hash = 0;
  for (int i = 0; i < s.length( ); i++)
  {
    hash = hash + s[i];
  }
  return hash % SIZE;  // SIZE = 10 in example
}

Example:  "dog" = ASCII 100, 111, 103
Hash = (100 + 111 + 103) % 10      =  4
```

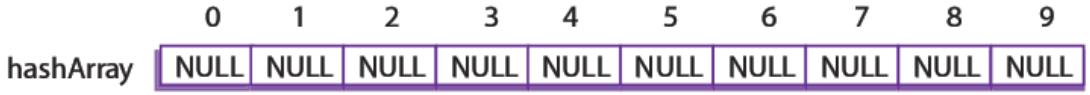
# Hash Table Idea

- Storage
  - Make an array of fixed size, say 10
  - In each array element store a linked list
  - To add an item, map (i.e. hash) it to one of the 10 array elements, then add it to the linked list at that location
- Retrieval
  - To look up an item, determine its hash code then search the linked list at the corresponding array slot for the item

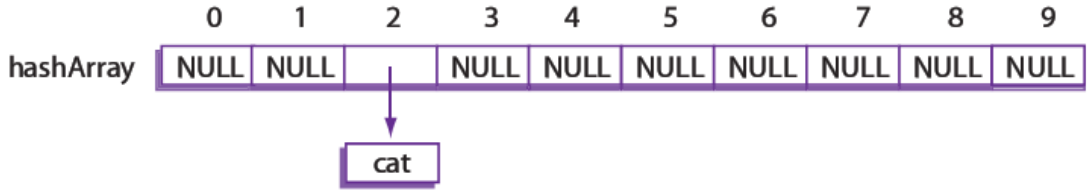
# Constructing a Hash Table

Existing hash table with 10 empty linked lists

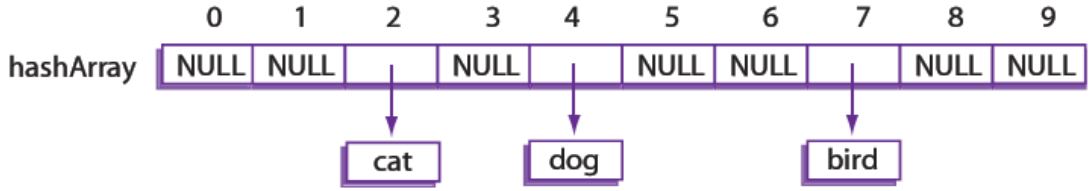
```
Node<string> *hashArray[10];
for (int i=0; i<10; i++) hashArray[i] = NULL;
```



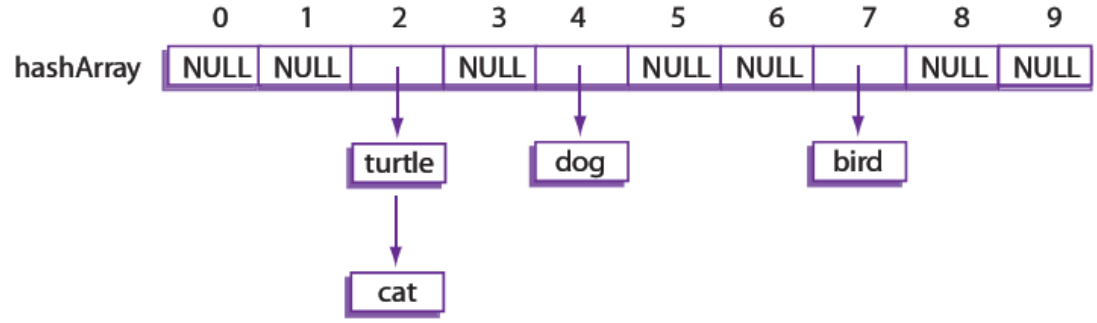

After adding "cat" with a hash of 2




After adding "dog" with a hash of 4 and "bird" with a hash of 7




After adding "turtle" with a hash of 2 - collision and chained to linked list with "cat"



# Interface File for a HashTable Class (1 of 2)

```
 1  // This is the header file hashtable.h.  This is the interface
 2  // for the class HashTable, which is a class for a hash table
 3  // of strings.
 4  #ifndef HASHTABLE_H
 5  #define HASHTABLE_H

 6  #include <string>
 7  #include "listtools.h"
```

*The library "listtools.h" is the linked list library interface from Display 17.14.*

```
 8  using LinkedListSavitch::Node;
 9  using std::string;

10  namespace HashTableSavitch
11  {
12   const int SIZE = 10;  // Maximum size of the hash table array
```

# Interface File for a HashTable Class (2 of 2)

```
13   class HashTable
14   {
15    public:
16        HashTable(); // Initialize empty hash table
17        // Normally a copy constructor and overloaded assignment
18        // operator would be included.  They have been omitted
19        // to save space.
20        virtual ~HashTable();  // Destructor destroys hash table

21        bool containsString(string target) const;
22        // Returns true if target is in the hash table,
23        // false otherwise

24        void put(string s);
25        // Adds a new string to the hash table

26    private:
27        Node<string> *hashArray[SIZE];      // The actual hash table
28        static int computeHash(string s);   // Compute a hash value
29   }; // HashTable
30  } // HashTableSavitch
31  #endif // HASHTABLE_H
```

# Implementation File for Hash Table Class (1 of 3)

```
 1  // This is the implementation file hashtable.cpp.
 2  // This is the implementation of the class HashTable.

 3  #include <string>
 4  #include "listtools.h"
 5  #include "hashtable.h"

 6  using LinkedListSavitch::Node;
 7  using LinkedListSavitch::search;
 8  using LinkedListSavitch::headInsert;
 9  using std::string;

10  namespace HashTableSavitch
11  {
12    HashTable::HashTable()
13    {
14     for (int i = 0; i < SIZE; i++)
15     {
16      hashArray[i] = NULL;
17     }
18 }
```

# Implementation File for Hash Table Class (2 of 3)

```
19    HashTable::~HashTable()
20    {
21      for (int i=0; i<SIZE; i++)
22      {
23        Node<string> *next = hashArray[i];
24        while (next != NULL)
25        {
26          Node<string> *discard = next;
27          next = next->getLink( );
28          delete discard;
29        }
30      }
31    }

32    int HashTable::computeHash(string s)
33    {
34     int hash = 0;
35     for (int i = 0; i < s.length( ); i++)
36     {
37      hash = hash + s[i];
38     }
39     return hash % SIZE;
40    }
```

# Implementation File for Hash Table Class (3 of 3)

```
41    void HashTable::put(string s)
42    {
43     int hash = computeHash(s);
44     if (search(hashArray[hash], s)==NULL)
45     {
46       // Only add the target if it's not in the list
47       headInsert(hashArray[hash], s);
48     }
49    }
50 } // HashTableSavitch
```

# Hash Table Demonstration

```
 1  // Program to demonstrate use of the HashTable class
 2  #include <string>
 3  #include <iostream>
 4  #include "hashtable.h"
 5  #include "listtools.cpp"
 6  #include "hashtable.cpp"
 7  using std::string;
 8  using std::cout;
 9  using std::endl;
10  using HashTableSavitch::HashTable;

11  int main()
12  {
13    HashTable h;
14    cout << "Adding dog, cat, turtle, bird" << endl;
15    h.put("dog");
16    h.put("cat");
17    h.put("turtle");
18    h.put("bird");
19    cout << "Contains dog? " << h.containsString("dog") << endl;
20    cout << "Contains cat? " << h.containsString("cat") << endl;
21    cout << "Contains turtle? " << h.containsString("turtle") << endl;
22    cout << "Contains bird? " << h.containsString("bird") << endl;
23    cout << "Contains fish? " << h.containsString("fish") << endl;
24    cout << "Contains cow? " << h.containsString("cow") << endl;
25    return 0;
26  }
```

**SAMPLE DIALOGUE**

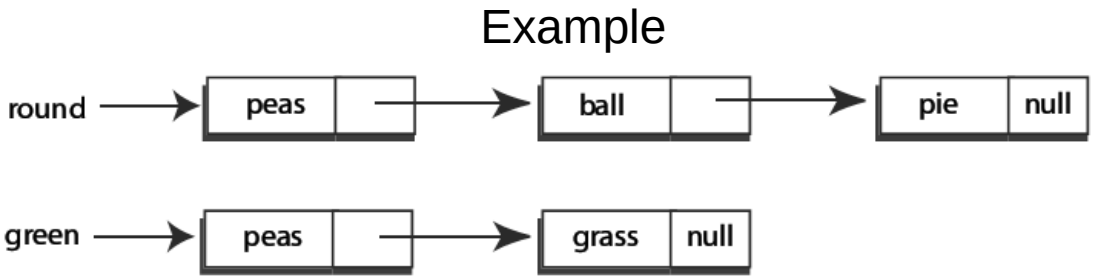
```
Adding dog, cat, turtle, bird
Contains dog? 1
Contains cat? 1
Contains turtle? 1
Contains bird? 1
Contains fish? 0
Contains cow? 0
```

# Hash Table Efficiency

- Worst Case
  - Every item inserted into the table has the same hash key, the find operation may have to search through all items every time (same performance as a linked list)
- Best Case
  - Every item inserted into the table has a different hash key, the find operation will only have to search a list of size 1, very fast
- Can decrease the chance of collisions with a better hash function
- Tradeoff:  Lower chance of collision with bigger hash table, but more wasted memory space

# Set Template Class

- A set is a collection of elements in which no element occurs more than once
- We can implement a simple set that uses a linked list to store the items in the set
- Fundamental set operations we will support:
  - Add
  - Contains
  - Union
  - Intersection



# Interface File for a Set Template Class (1 of 2)

```
 1  // This is the header file set.h.  This is the interface
 2  // for the class Set, which is a class for a generic set.
 3  #ifndef SET_H
 4  #define SET_H
 5  #include "listtools.h"
    "listtools.h" is the linked list library interface from Display 17.14.
 6  using LinkedListSavitch::Node;

 7  namespace SetSavitch
 8  {
 9    template<class T>
10    class Set
11    {
12     public:
13        Set() { head = NULL; } // Initialize empty set

14        // Normally a copy constructor and overloaded assignment
15        // operator would be included.  They have been omitted
16        // to save space.

17        virtual ~Set();  // Destructor destroys set
```

# Interface File for a Set Template Class (2 of 2)

```
18        bool contains(T target) const;
19        // Returns true if target is in the set, false otherwise

20        void add(T item);
21        // Adds a new element to the set

22        void output();
23        // Outputs the set to the console

24        Set<T>* setUnion(const Set<T>& otherSet);
25        // Union calling object's set with otherSet
26        // and return a pointer to the new set

27        Set<T>* setIntersection(const Set<T>& otherSet);
28        // Intersect calling object's set with otherSet
29        // and return a pointer to the new set
30     private:
31        Node<T> *head;
32    }; // Set
33  } // SetSavitch
34  #endif // SET_H
```

# Implementation File for a Set Template Class (1 of 4)

```
 1  // This is the implementation file set.cpp.
 2  // This is the implementation of the class Set.
 3  #include <iostream>
 4  #include "listtools.h"
 5  #include "set.h"
 6  using std::cout;
 7  using std::endl;
 8  using LinkedListSavitch::Node;
 9  using LinkedListSavitch::search;
10  using LinkedListSavitch::headInsert;
11  namespace SetSavitch
12  {
13     template<class T>
14     Set<T>::~Set()
15     {
16         Node<T> *toDelete = head;
17         while (head != NULL)
18         {
19           head = head->getLink( );
20           delete toDelete;
21           toDelete = head;
22         }
23     }
```

# Implementation File for a Set Template Class (2 of 4)

```
24    template<class T>
25    bool Set<T>::contains(T target) const
26    {
27     Node<T>* result = search(head, target);
28     if (result == NULL)
29        return false;
30     else
31        return true;
32    }

33    void Set<T>::output()
34    {
35        Node<T> *iterator = head;
36        while (iterator != NULL)
37        {
38          cout << iterator->getData( ) << " ";
39          iterator = iterator->getLink( );
40        }
41        cout << endl;
42    }
```

# Implementation File for a Set Template Class (3 of 4)

```
43      template<class T>
44      void Set<T>::add(T item)
45      {
46       if (search(head, item)
          ==NULL)
47       {
48         // Only add the target if
              it's not in the list
49         headInsert(head, item);
50       }
51      }
```

```
52      template<class T>
53      Set<T>* Set<T>::setUnion(const
                  Set<T>& otherSet)
54      {
55       Set<T> *unionSet = new Set<T>();
56       Node<T>* iterator = head;
57       while (iterator != NULL)
58       {
59        unionSet->add(iterator->getData(
));
60        iterator = iterator->getLink( );
61       }
62       iterator = otherSet.head;
63       while (iterator != NULL)
64       {
65        unionSet->add(iterator->getData(
));
66        iterator = iterator->getLink( );
67       }
68       return unionSet;
69      }
```

# Implementation File for a Set Template Class (4 of 4)

```
70      template<class T>
71      Set<T>* Set<T>::setIntersection(const Set<T>& otherSet)
72      {
73       Set<T> *interSet = new Set<T>();
74       Node<T>* iterator = head;
75       while (iterator != NULL)
76       {
77          if (otherSet.contains(iterator->getData( )))
78          {
79           interSet->add(iterator->getData( ));
80          }
81          iterator = iterator->getLink( );
82       }
83       return interSet;
84      }
85  } // SetSavitch
```

# Set Demonstration (1 of 3)

```
 1  // Program to demonstrate use of the Set class
 2  #include <iostream>
 3  #include <string>
 4  #include "set.h"
 5  #include "listtools.cpp"
 6  #include "set.cpp"
 7  using std::cout;
 8  using std::endl;
 9  using std::string;
10  using namespace SetSavitch;
11  int main()
12  {
13        Set<string> round;   // Round things
14        Set<string> green;   // Green things

15        round.add("peas");   // Sample data for both sets
16        round.add("ball");
17        round.add("pie");
18        round.add("grapes");
19        green.add("peas");
20        green.add("grapes");
21        green.add("garden hose");
22        green.add("grass");
```

# Set Demonstration (2 of 3)

```
23        cout << "Contents of set round: ";
24        round.output();
25        cout << "Contents of set green: ";
26        green.output();

27        cout << "ball in set round? " <<
28                round.contains("ball") << endl;
29        cout << "ball in set green? " <<
30                green.contains("ball") << endl;

31        cout << "ball and peas in same set? ";
32        if ((round.contains("ball") && round.contains("peas")) ||
33            (green.contains("ball") && green.contains("peas")))
34            cout << "  true" << endl;
35        else
36            cout << "  false" << endl;

37        cout << "pie and grass in same set? ";
38        if ((round.contains("pie") && round.contains("grass")) ||
39            (green.contains("pie") && green.contains("grass")))
40            cout << "  true" << endl;
41        else
42            cout << "  false" << endl;
```

# Set Demonstration (3 of 3)

```
43          cout << "Union of green and round: " << endl;
44          Set<string> *unionset = round.setUnion(green);
45          unionset->output();
46          delete unionset;

47          cout << "Intersection of green and round: " << endl;
48          Set<string> *interset = round.setIntersection(green);
49          interset->output();
50          delete interset;

51          return 0;
52      }
```

**SAMPLE DIALOGUE**

```
Contents of set round: grapes pie ball peas
Contents of set green: grass garden hose grapes peas
ball in set round? 1
ball in set green? 0
ball and peas in same set?   true
pie and grass in same set?   false
Union of green and round:
garden hose grass peas ball pie grapes
Intersection of green and round:
peas grapes
```

# Friend Classes

- Recall constant use of getLink and setlink accessor and mutator functions
  - Somewhat of a nuisance
  - Similar to making data public?!
    - Public makes available to ALL!
- Use friend class
  - Make queue template class "friend" of node template class
  - All private link members directly available in member functions of queue class!

# Forward Declaration

- Class friendships typically require classes reference each other
  - Presents problem
  - How can "both" be declared at same time?
- Requires forward declaration
  - Simple class heading given inside other:
    class Queue;  //Forward Dec.
  - Announces "class Queue will exist"

# Iterators

- Construct for cycling through data
  - Like a "traversal"
  - Allows "whatever" actions required on data
- Pointers typically used as iterators
  - Seen in linked list implementation

# Pointers as Iterators

- Recall: linked list: "prototypical" data structure
- Pointer: "prototypical" example of iterator
  - Pointer used as iterator by moving thru linked list node by node starting at head:
  - Example:

```
Node_Type *iterator;
for (iterator = Head; iterator != NULL;
                                iterator=iterator->Link)
  Do_Action
```

# Iterator Classes

- More versatile than pointer
- Typical overloaded operators:

  | | |
  |---|---|
  | ++ | advances iterator to next item |
  | -- | retreats iterator to previous item |
  | == | Compares iterators |
  | != | Compare for not equal |
  | * | Accesses one item |

- Data structure class would have members:
  begin(): returns iterator to 1st item in structure
  end(): returns iterator to test if at end

# Iterator Class Example

- Cycle through data structure named *ds*:

```
for (i=ds.begin();i!=ds.end();i++)
    process *i  //*i is current data item
```

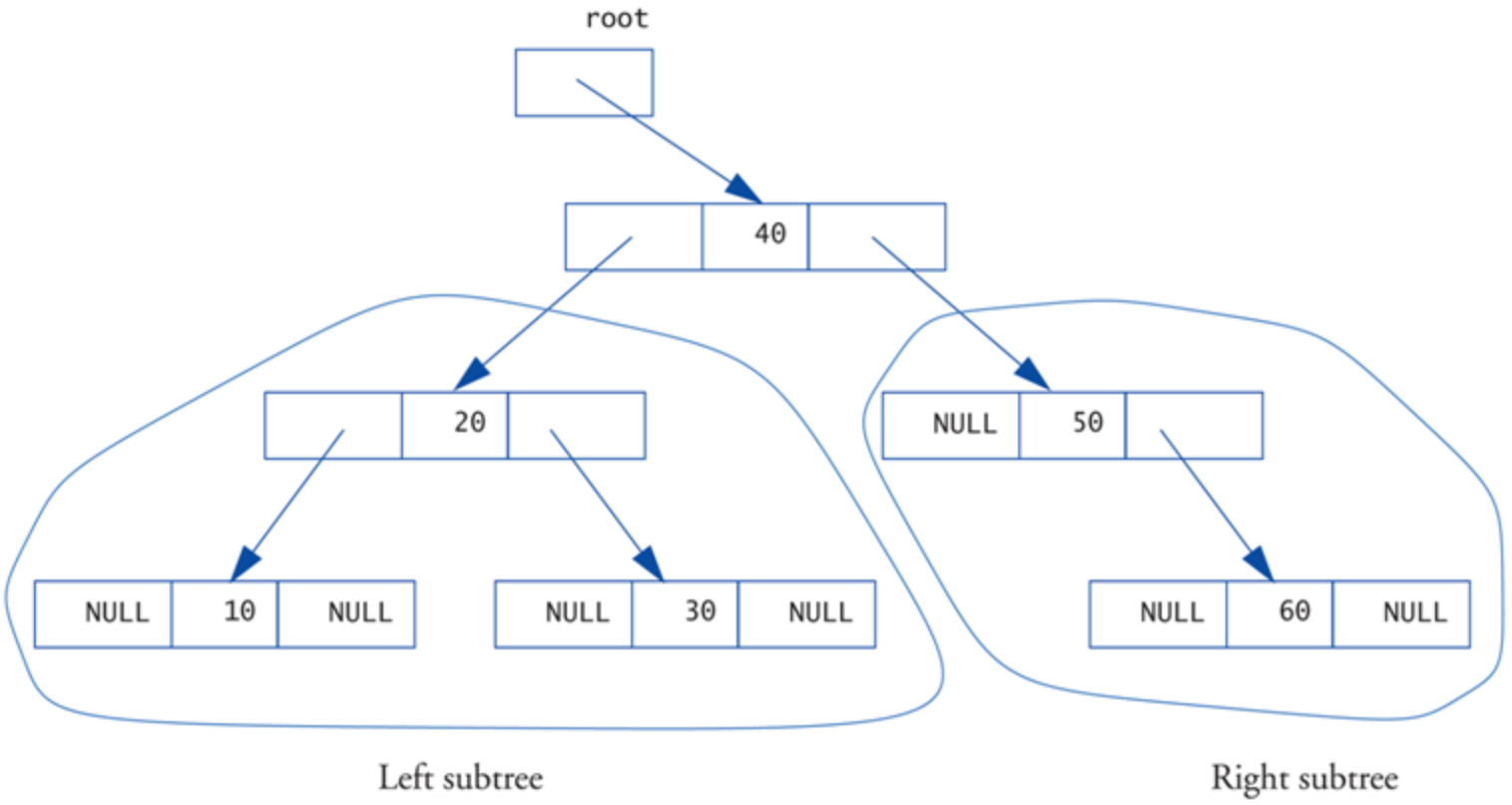
- i is name of iterator

# Trees Introduction

- Trees can be complex data structures
- Only basics here:
  - Constructing, manipulating
  - Using nodes and pointers
- Recall linked list: nodes have only one pointer → next node
- Trees have two, & sometimes more, pointers to other nodes

# Tree Structure:
# **Display 17.35** A Binary Tree (1 of 2)

**A Binary Tree**



# Tree Structure:
# **Display 17.35** A Binary Tree (2 of 2)

```
class IntTreeNode
{
public:
    IntTreeNode(int theData, IntTreeNode* left, IntTreeNode* right)
        : data(theData), leftLink(left), rightLink(right){}
private:
    int data;
    IntTreeNode *leftLink;
    IntTreeNode *rightLink;
};


IntTreeNode *root;
```

# Tree Properties

- Notice paths
  - From top to any node
  - No "cycles" – follow pointers, will reach "end"
- Notice here each node has two links
  - Called ***binary tree***
  - Most common type of tree
- Root node
  - Similar to linked list's head
- Leaf nodes
  - Both link variables are NULL (no subtrees)

# Trees and Recursion

- Note tree's "recursive structure"
- Each tree has two subtrees
  - Each subtree has two subtrees
    - Etc., etc.
- Makes trees amenable to recursive algorithms
  - For searching especially!

# Tree Processing

- **Preorder Processing:**
  1. Process data in root node
  2. Process left subtree
  3. Process right subtree
- **In-order Processing:**
  1. Process left subtree
  2. Process data in root
  3. Process right subtree
- **Postorder Processing:**
  1. Process left subtree
  2. Process right subtree
  3. Process data in root

# Tree Storage

- Our example stored values in special way:
  - Called binary search tree storage rule:
    1. values in left subtree less than root value
    2. values in right subtree greater than root
    3. rule applies recursively to each subtree
- Trees using this storage mechanism:
  - Called binary search tree (BST)
  - Traversals:
    Inorder → values "in order"
    Preorder → "prefix" notation
    Postorder → "postfix" notation

# Summary 1

- Node is struct or class object
  - One or more members is pointer
  - Nodes connected by member pointers
    - Produce structures that grow and shrink at runtime
- Linked list
  - List of nodes where each node points to next
  - In a doubly linked lists there are pointers in both directions
- End of linked list marked with NULL pointer

# Summary 2

- Stack is LIFO data structure
- Queue is FIFO data structure
- Hash Tables are data structures for quick storage and retrieval; can be implemented with a linked list
- Sets can be implemented with linked lists
- Iterator construct allows cycling through data items in given data structure
- Tree data structures
  - Nodes have two member pointers
  - Each point to other nodes/subtrees
- Binary search tree
  - Special storage rules allow rapid searches